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System boundary for embodied energy in buildings: A conceptual model for definition

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ABSTRACT

Buildings consume nearly 40% of global energy annually in their production, operation, maintenance, replacement and demolition stages. Energy consumed in their life cycle stages other than the operation is called life cycle embodied energy. Total life cycle energy constitutes the building's embodied and operational energy over its service life. Operational energy constitutes a relatively larger fraction of life cycle energy in a conventional building. However, with the emergence of larger number of low energy buildings the significance of embodied energy is expected to grow. Current embodied energy calculations exhibit problems of variation, inaccuracy and incompleteness. System boundary definition is a key parameter that differs across studies and causes these problems, as studies define their system boundary subjectively. Research studies have proposed various system boundary models that should be applied to the buildings for life cycle analysis; however, the extent of their boundary definition differs. This paper gathers and synthesizes relevant literature opinions to develop a comprehensive system boundary model that can be adopted while performing the life cycle energy analysis of a building. The purpose of developing this model is twofold. Firstly, it would provide a clear picture of the system boundary. Second, it would provide a model to quantify the embodied energy of a building. Three possible approaches to cover the proposed system boundary are also recommended.

Contents

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1. Introduction

The building sector consumes 40% of energy and 16% of water each year globally during building's life cycle stages of material processing and manufacturing, transportation, construction, operation, maintenance, replacement, demolition and disposal. Energy consumed in life cycle stages other than the operation is called the embodied energy of a building [1,2]. Energy expended during the building operation phase in space conditioning, water heating, lighting, operating building appliances and other similar operational activities is known as operational energy. The building's total life cycle energy consists of total operational and embodied energy [1,3]. Compared to embodied energy, operational energy constitutes a relatively larger proportion of a building's total life cycle energy [3]. However, recent research has acknowledged the significance of embodied energy and has indicated that with the growing emergence of more energy efficient buildings the relative proportion of embodied energy may increase [4–6]. Sartori and Hestnes [7] concluded that for a conventional building the embodied energy could account for 2–38% of the total life cycle energy and for a low energy building, this could range from 9–46%. Thormark [8] determined that the embodied energy of a low energy house could be equal to 40–60% of the total life cycle energy. Black et al. [9] have pointed out a relationship between the energy use in buildings and greenhouse gas emissions, thus underscoring the environmental significance of embodied energy.

Previous studies of embodied energy analysis and computation exhibit variation in embodied energy results owing to numerous factors [2,6,10–12]. Embodied energy values in building materials and buildings could possess variation up to 30–50% [13]. Furthermore, other studies pointed out the inaccuracy and incompleteness of existing embodied energy data relating to building materials [13–15]. These issues with energy data make the comparison of building materials and products difficult in embodied energy terms [15]. Inaccurate, incomplete and inconsistent data cannot be used for the environmental decision making by building professionals such as designers, engineers, project managers and contractors while selecting low energy building materials [16]. There exist parameters that cause embodied energy values to differ across research studies [15]. Most of these parameters are related to the embodied energy analysis or Life Cycle Assessment (LCA) methods; some of them are actually data quality related issues. Incompleteness, inaccuracy and no-representativeness are primary data quality related parameters that are responsible for inconsistency in energy results. Among the key methodological parameters are differing system boundary definition, embodied energy measurement method, energy terms and energy inputs [15,17,18].

System boundary definition has been an important issue of discussion in existing literature [19]. The literature [20–23] exhibits differences of opinion on the extent of the system boundary to be adopted. Furthermore, which energy and material inputs to include in the analysis is not always clear and consistent and as a result studies select boundary definitions subjectively [17,24–29]. System boundaries in studies differ in three ways. First, studies often include only one or few life cycle stages of a building in the embodied energy analysis [2,30]. The transportation and transformation processes between two consecutive life cycle stages are seldom considered in the calculation. Second, how far in the upstream and downstream of each life cycle stage a study should go is unclear [19,27,29]. Finally, not all studies consider the whole building in the embodied energy calculation and cover one or few building components such as building structure, envelope, finishes, services, site features etc. [2,12,30]. These differences of system boundary result in problems of variation and incompleteness due to exclusion of important life cycle stages or building components from the energy analysis [2,31]. Literature [3,32] pointed out certain issues such as inclusion of human energy, feedstock energy of materials and renewable energy that need to be clarified. Some studies [1,33,34] emphasized energy and resource recovery at the end of life, some do not. Few studies [35,36] covered processes such as transportation for materials and equipment as well as labor. Others were limited to material transportation only. Raynolds et al. [37] emphasize the need for a system that ensures consistent system boundary selection across different studies. Capper et al. [24], Abanda et al. [17], Chang et al. [18] and Deng et al. [38] suggested building a consensus on the issue of a consistent system boundary definition. The situation clearly indicates a need to gather and synthesize literature opinion and build a model for system boundary definition.

This paper contains a literature survey of key contributions from system boundary studies. A conceptual model was then developed as a multi-layered system boundary model.

2. Literature review

Extensive literature exists on system boundary model for life cycle energy analysis of a building. The review of literature presented here discusses the system boundary defined in the life cycle stage terms, input and output to each stage terms and building components terms (upstream and downstream of a building).

2.1. System boundary: overview

The system boundary demarcates a system of various products and processes related to the manufacturing of a product under study. A system boundary also determines the number and type of energy and material inputs and waste and emission outputs that are included in the embodied energy calculation of a particular product [39,40]. A system boundary for a product could range from raw material extraction for its manufacturing in distant upstream to demolition and its disposal furthest downstream. Among common system boundaries for buildings and building products are "cradle to gate", "cradle to site" and "cradle to grave." The cradle to gate system boundary includes upstream processes such as raw material extraction through a point where the finished product leaves the factory gate (excluding transport of material to the building site) [6,41]. The cradle to site covers, in addition to the cradle to gate boundary, transportation of finished product to the construction site, construction and assembly processes on-site, wastage disposal etc. [42]. The cradle to grave system boundary takes into account the use phase with operations and maintenance, renovation and refurbishment and retrofit activities. The end of life phase with processes such as building demolition, waste sorting and hauling, recycling and reuse, and disposal of discarded waste to landfills is also included [23,42]. The cradle to grave boundary provides a whole life cycle perspective, which is important for a comprehensive and genuine environmental assessment [5,23,31,36]. The following sections discuss the various stages of a building's life cycle that become a part of its system boundary definition.

2.2. Building system boundary: life cycle stages

2.2.1. Building material production stage

The building material manufacturing process consumes energy and resources such as feedstock materials and water [43]. The main production process consumes direct energy and raw

materials, whereas upstream processes of raw material extraction, processing and transportation to the manufacturing unit also contribute to the embodied energy. After a building product is manufactured, it is packaged, stored and transported to a vending agency or a construction site and all these downstream processes also involve energy consumption [2,23,36]. The energy sequestered in this stage shares the largest fraction of a building's life cycle embodied energy [36,44,45]. The energy embodied in the production of building materials can be reduced drastically if strategies such as use of recycled material are applied [34,44,46,47]. Chen et al. [44] reported that the recycled steel (10 MJ/kg) and aluminum (8 MJ/kg) could conserve at least 70% and 96% of production energy respectively as compared to the virgin steel (32 MJ/kg) and aluminum (191 MJ/kg). Recycling at this stage could be either preconsumer or postconsumer recycling. In a preconsumer recycling, materials are recycled within the same manufacturing chain, whereas in a post-consumer recycling, recycled material may be sourced externally [31,48,49]. Postconsumer recycled materials may come from what Treloar et al. [50] and Thormark [33] defined an open loop recycling that occurs between industries or between life cycle phases of a building. A closed loop recycling involves materials to be recycled within the same industry and such materials are known as preconsumer recycled materials [33,45,50,51]. Use of recycled materials at this stage could save a minimum of 60% of a building's initial embodied energy [44].

2.2.2. *Transportation from production unit to point of use*

The finished building materials are transported to construction sites or to suppliers, which may be located in the same country or overseas. Hence, building materials could be distributed locally or exported to other locations involving a variety of transportation modes and consuming energy [39,44,52,53]. Building materials and products may be hauled to their points of use by surface (road and rail), water (boats and ships) or air depending on the destination [39,44]. Studies such as [44] reported that energy use in domestic surface transportation of building material could be nearly negligible, whereas exporting or importing products could involve considerable energy consumption. However, in an analysis of modular homes, Kim [54] found that transportation energy involved in building construction was nearly 8% of its total embodied energy. Peuportier [39] questioned that whether return trips of vehicles should be considered on a one-way trip, as it is most likely that vehicles (e.g. trucks) may return empty. The author eventually considered only half of the return distance, as chances of trains and ships returning empty after material deliveries are highly unlikely. Miller [52] reported that if return distance and road infrastructure are considered, the energy embodied in transporting building materials may increase drastically.

2.2.3. *Construction stage*

Energy sequestered during the construction phase of a building is consumed mainly in transportation and construction operation activities on-site and off-site. Resources such as labor, materials, equipment and machinery that are transported during the construction phase incorporate energy consumption [35,36]. A major amount of energy (69% of the total construction energy) is used in transportation processes involved during this stage [55]. Pullen [55] found that at least 3% of construction energy can be attributed to labor and 28% to equipment. In some geographic locations, conventional construction processes are labor intensive and involve considerable amount of human energy [56–58]. However, Gao et al. [47] mentioned that human energy may be much smaller than mechanical energy and reported that one liter of diesel could be equivalent to two humans working over six days. A large amount of waste is generated during transportation and transformation of building materials during the construction process [44,50]. Energy which is embedded in construction waste could be significant and could carry adverse environmental impacts if not taken care of properly [36,50]. The amount of waste generated in the construction processes depends on a waste factor, which is the percentage of material that may be wasted [34,50,59,60]. The waste factor depends on the type of material used and studies have derived different waste factors for different building materials. Table 1 presents various waste factors derived by various studies for different building materials. Materials can also be reused in the construction process without changing its current form and nature [44,46]. Building products that are made of materials such as wood and metals can be reused for the same or different purpose. Demolition or construction waste that includes concrete and brick can be reused as gravel in the construction of buildings [46].

2.2.4. *Maintenance and replacement stage*

The building's use phase encompasses operational activities as well as maintenance, repair and replacement processes, which consume a large amount of energy and resources. Energy used in maintenance and replacement activities is termed as recurrent or recurring energy [31,61,62]. According to Cole and Kernan [63], a building material or component replaced 100% falls in the category of replacement and any replacement less than 100% is covered under maintenance. Building materials and components may not possess the same service life as the building and may require one or multiple replacements over the building's service

Table 1
Waste factors suggested by various studies.

Building materials	Adalberth [59]	Chen et al. [44]	Treloar et al. [50]	Worth et al. [34]	Chau et al. [49]	Blengini [60]
Steel	5%	5%	5%	6%[a]	5%	7%
Aluminum	–	2.5%	10%[a]	6%[a]	5%	5%
Copper	5%	2.5%	10%[a]	6%[a]	5%	5%
Concrete	10%	2.5%	5%	–	3%	7%
Glass	0	0	3%	–	5%	7%
Brick		–	5%[b]	–	3%	10%
Insulation	5–10%	5%	–	6%	8%	7%
Finishes e.g. *paints*	5%	–	5%	0	5%	7%
Plaster	–	–	10%		5%	10%
Timber	10%	2.5%	10%	11%	–	7%
Plastic	–	5%	10%		3–5%	7%
Equipment	–	–	0	–	–	–

[a] % indicated for metals in actual study.
[b] % indicated for masonry/clay in actual study.

life [44,49,61,64]. These replacements, as in the building erection phase, require building materials, products and construction processes [65]. Each of these products and processes contributes to the embedded energy [8,44,62,66]. Building components such as the envelope, finishes and the services, which may not hold higher embodied energy initially, require a significant recurring energy (3.2 times the initial embodied energy in 50-year service life) [61]. Recurrent energy over 60 years of building service life is found to be at least 72% of its total life cycle embodied energy in a case study of Australian Secondary Schools [62]. A replacement factor, which is the ratio of service life of a building to average service life of a building material or a component, could be decisive in determining the amount of recurrent embodied energy [44,49]. Functional, aesthetical and end of service life of associated components are primary reasons for most replacements occurring in a building [64]. Fashion is also seen as a major reason behind frequent replacements of building elements such as furniture, fixtures and fittings [67]. Table 2 presents the replacement factors for some of the building materials and components as determined by various studies.

2.2.5. Demolition stage

Demolishing a building and disposing of its waste materials at the end of its useful life involves processes that are energy intensive. Energy consumed in various processes of building demolition, waste handling and sorting, recycling and reuse, and waste disposal to landfill or incinerator is known as demolition energy [1,36,52,60,63,64,70]. Energy at this stage is consumed in four stages. The first stage involves complete demolition and disassembly of the building and utilizes heavy equipment such as hydraulic hammers and hydraulic loaders that consume energy [52,60]. In the second stage, on-site secondary demolition occurs, the purpose of which is to separate building materials and reduce their sizes for easy handling and sorting. Waste as well as salvaged materials are then transported to either landfills or to reuse and recycling facilities at the third stage. Finally, equipment such as jaw crushers and magnetic separators are used to separate and salvage reusable and recyclable materials at the recycling facilities. Sorted reusable or recyclable materials are then transported to manufacturing facilities or construction sites by means of trucks and trains [60]. One important activity at this stage includes recycling and reuse processes that could recover a major fraction of initial energy embodied in the building [1,51]. Recycling and reuse may be an open loop or a closed loop type process [51]. In an open loop materials are recycled or reused between industries or life cycle stages of a building, whereas closed loop involves recycling and reuse within the same industry or life cycle stage [33,50].

2.3. Building system boundary: upstream and downstream of life cycle stages

Each of the system boundary definitions (e.g. cradle to gate, cradle to grave, cradle to cradle etc.) differs in the width of the system boundary in each life cycle stage of a building. Studies that covered the whole life cycle in embodied energy analysis could differ in the extent to which energy and material inputs are covered in the distant upstream and downstream of each life cycle stage [10,14,71]. Capital infrastructure required at each stage (e.g. manufacturing plant buildings and machines) also possesses energy sequestered which should also be accounted for. In addition, production and construction processes are more labor intensive in some locations which necessitates considering human energy in embodied energy calculations [56–58,71]. Each life cycle stage also includes the input of energy and products and the output of waste and emission to air, land and water [20,31,49,72,73]. Each energy input is either in a primary or a delivered energy form and possesses its own energy cost of acquisition, storage and distribution that also need to be covered in the embodied energy calculations [35,68]. Product inputs may include not only feedstock material but also equipment, vehicles and permanent or temporary built facilities [22,39]. However, according to Peuportier [34] energy embedded in capital buildings, equipment and vehicles may be negligible. Energy and products are also used while addressing adverse environmental impacts caused by waste and emissions [21,74].

2.4. Building system boundary: upstream and downstream of buildings

Emphasis of embodied energy calculation for buildings could be on the whole building or on a few components [12]. Studies such as [2,4,61,75–77] covered the entire building in the embodied energy calculation, whereas only one or more building components are analyzed by Cole [78], Pierquet et al. [79], Vegh [80], Goggins et al. [41] and Crawford et al. [81]. Moreover, building elements such as furniture, fittings and fixtures not only have a higher initial embodied energy but also possess a high recurrent energy due to frequent replacements [67]. Building site components such as outbuildings, landscaping and fencing also contribute towards a building's total embodied energy [62]. Building as a final product also requires infrastructure that encompasses roads, walkways, parks, sewerage, storm water, utilities etc. Buildings carry their share of total energy embedded in these infrastructure components also, which should be included in embodied energy calculations [82–85]. Relatively limited studies exist that emphasize accounting for embodied impacts of infrastructure. Pullen [86], Troy et al. [83], Pullen [84]

Table 2
Replacement factors suggested by literature.

Building component	Treloar et al. [67]	Fay et al. [68]	Chen et al. [44]	Keoleian et al. [69]	Scheuer et al. [45]	Chau et al. [49]	Ding [62]
Structure	1		1		1	1	
Ext./Int. walls	1.1		1		1	1	1–2.4
Doors			1.3		1.5		1.5–2
Windows		2	1.3	2	1.9		1.5
Wall/Roof tiles		2–4	1.3	2	3.75[a]	2.5[a]	2.4
Paints and Coat.	8	10	5	5	15	5	6–8.6
Carpet			2.4	6.2	6.25	3.3	5
Ceiling finishes	2		2		3.75	2.5[a]	4
Floor Finishes	4		3	2.5[b]	4.16[b]	2.5[b]	3[b]
Insulation					1	1	

[a] denotes acoustical tiles.
[b] indicates vinyl flooring.

and Panicot [85] have performed impressive embodied energy analyses of buildings to include energy sequestered in infrastructure at neighborhood and city scale. However, most of these studies are focused on locations around Australia.

2.5. System boundary model

Miller [52] and Khasreen et al. [31] assert that the research studies often do not describe the system boundary adopted in the study clearly and it becomes difficult for the readers to determine what is included and excluded from the energy calculation. Bekker [87] had suggested including all five phases of a building's life cycle that included mining and transporting raw materials, manufacturing building materials, constructing, operating, maintaining, renovating, demolishing and disposing processes. Treloar [88] suggested that the system boundary spread depends on the level of complexity of construction, as more complex construction may incorporate multiple (sometimes infinite) upstream processes that consume energy indirectly. Treloar [88] further explains that direct energy that is mainly consumed in the main construction process of a building is easily quantifiable. Indirect energy, however, could be embedded in finite or infinite upstream stages that may include input of goods and services. Costanza [89] and Herendeen [90] had expressed a similar opinion about direct and indirect inputs.

The International Federation of Institutes of Advanced Studies (IFIAS) organized a workshop on the relationship of energy and economic analysis that included 27 economists and scientists from ten countries around the globe [40]. The IFIAS workshop provided a simplified system boundary model with four levels of regression to include most of the energy and material inputs to a process under study. Fig. 1 illustrates the system boundary model as proposed in the IFIAS workshop. Level I regression includes only direct inputs of primary and delivered energy to the main process under study. Materials and energy (e.g. electricity) involved in the main process may also have consumed energy in their acquisition and production which is accounted for in level II regression. Level III analysis includes production energy required for direct energy input at level II as well as energy consumed in manufacturing capital equipment used in the main process. A level IV regression may include the production energy of machines that produced equipment and machines that are used in level III processes. Each of these levels also includes energy consumed in transportation [40]. Studies [23,42,91,92] have discussed various possible levels of system boundary definitions that are applicable to a building.

Atkinson [20] suggested that each product or material under study should be traced from its manufacturing stage back to and forward to the biosphere (nature) as shown in Fig. 2. The author also discussed that each phase of a building's life cycle involves output of solid, liquid or gaseous waste and emission affecting the ecosystems. A careful look at a simplified model suggested by Atkinson [20] reveals the upstream and downstream processes denoting tracing back and forward to nature (see Fig. 2). Edwards and Bennett [74] proposed a boundary definition that reports a building's life cycle as a product system, upstream of which covers all water, primary and delivered energy inputs and their acquisition. Resulting wastes and emissions are shown in the downstream (see Fig. 3). Likewise, Ries and Mahdavi [21] formulated and proposed a boundary definition that incorporates land use attached with life cycle stages in addition to the energy embodied in capital infrastructure required (see Fig. 4).

Earlier, Buchanan and Honey [91] and recently Hammond and Jones [23] discussed four levels of system boundary regression starting from the building as a finished product based on the IFIAS workshop model. According to these studies the first level of regression could include all direct energy inputs into the processes of a building's life cycle such as construction, prefabrication, maintenance, replacement, demolition and disposal. Energy sequestered into main and all upstream and downstream processes of building material and product manufacturing could be tracked as a second level of regression. Nearly 90% of the energy inputs could be tracked and determined by a second level of regression; however, this could not be guaranteed [23,40].

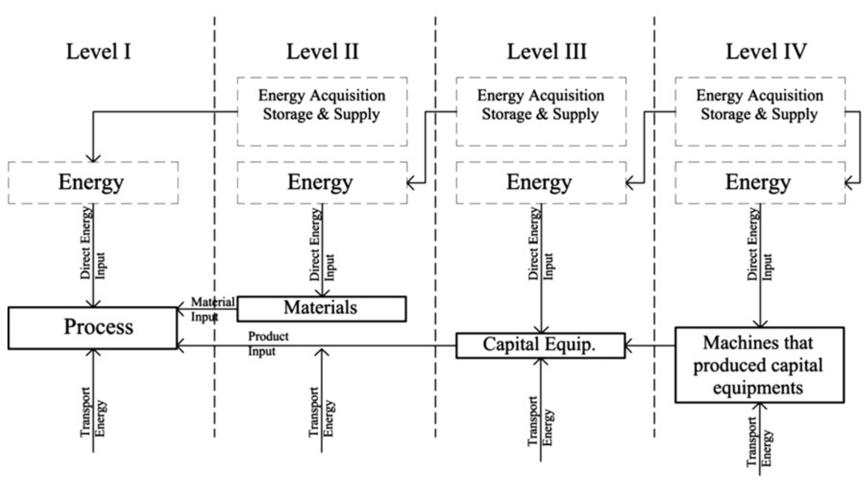

Fig. 1. System boundary model suggested by IFIAS [40].

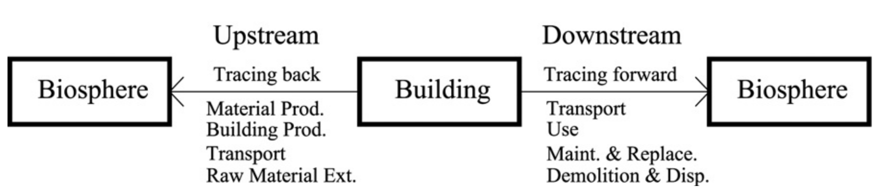

Fig. 2. Simplified system boundary model suggested by Atkinson [20].

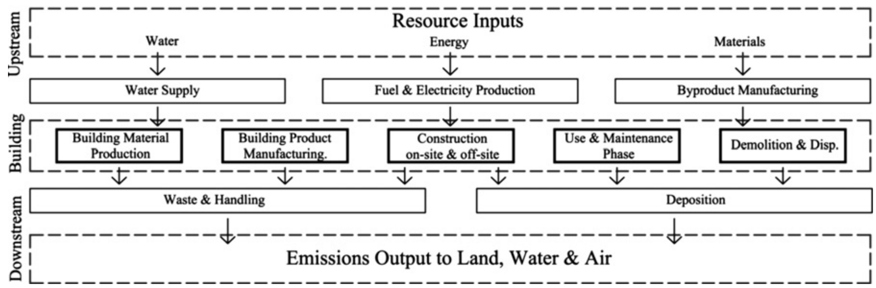

Fig. 3. Boundary definition derived by Edwards and Bennett [74].

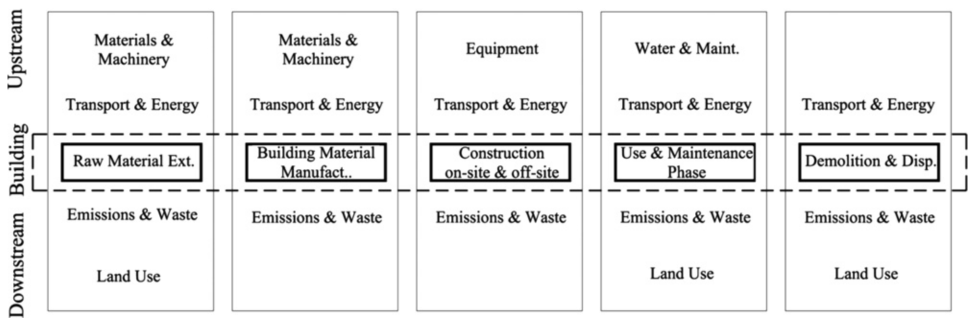

Fig. 4. System boundary for a building proposed by Ries and Mahdavi [21].

Furthermore, analysis of inputs beyond this level becomes time and effort consuming and as a result studies conducting analyses beyond this level are rare [23,42]. A third regression level could include energy embedded in production, delivery and installation of machines that are used in building materials manufacturing and on-site and off-site construction processes. Finally, machines that are utilized to produce machines (of third level regression) also consumed energy in their main, upstream and downstream production processes. This energy could be a part of a fourth level of regression. Each of these regression levels should include all energy inputs in the main and support processes related to product manufacturing. Fay [92] also expressed similar ideas about multiple system boundary definition levels. The fourth regression level, however, is the most difficult one and is hard to achieve [23,91]. Herendeen [90] illustrated a similar system boundary model by stating an example of car production. According to the author, 10% of total car production energy is consumed in the car manufacturing plant, whereas the remaining 90% energy is burned in acquiring, processing, producing and delivering its other constituent materials such as steel, plastic, glass etc. Moreover, the author revealed that 60% of the total energy to operate a car remains in its fuel tank but the remaining energy is embedded in its body, tires, roads and highways, petroleum refineries etc.

A model proposed by Chang et al. [18] included the embodied impacts of materials, appliances, transportation and construction that were used to deliver a building as a finished product. Deng et al. [38] proposed an interesting system in which all of the energy and material flows culminate into a stage that deals with waste reuse, recycle and treatment. Moreover, their model accounted for inputs such as food, human travel and consumables that are used to finish and furnish a building. Murphy et al. [93] suggested a multi-dimensional model that could be expanded up to five levels (inputs under study, energy inputs, material inputs, human labor and other supportive activities). Fig. 5 illustrates the system boundary model suggested by Murphy et al. [93]. An "extended system boundary" is another interesting concept of system boundary expansion proposed by Kua and Wong [82], which included impacts of managing waste that is produced during a building's operation. Studies such as Kua and Wong [82] and Matthews et al. [94] recommended expanding system boundaries beyond a building level to include impacts of its immediate surroundings.

3. Research purpose and method

From the review of current literature it is clear that the system boundary for life cycle embodied energy analysis of a building is defined with various lengths (that includes life cycle stages) and widths (that includes inputs and outputs in each stage). Some studies emphasized the importance of energy and materials recovery in their boundary definition; others focused more on capital infrastructure. Each of these studies resulted in a valuable contribution to embodied energy analysis. However, these results cannot be fully utilized, as their opinions remain fragmented. According to literature [e.g. 24,25,93] the system boundary definition is a crucial step in any life cycle analysis study and if boundaries differ across studies their results are not comparable. There is no agreement in the literature on a standard system boundary model and on inputs that should be included in a life cycle impact study [17,24,38,94]. In this paper, an effort was done to gather opinions relevant to system boundary definition from a variety of sources and synthesize them in order to formulate a comprehensive model for system boundary definition. This effort served two purposes. First, it presented a clear and comprehensive picture of what has been opined in literature about boundary definition so far. This model would help the research community decide whether this boundary definition could be feasible looking at the limitation of tracking and tracing energy and material inputs. Appropriate calculation methods then can be developed to include such an extensive boundary definition. Second, it would help in quantification of embodied energy of a building. Also, in order to make existing studies more useful, an empirical model of system boundary can be developed that facilitates energy data translation across differing scope levels (building material, component, whole building etc.). This paper used a Literature Based Discovery method (Dr. Don R. Swanson from the University of

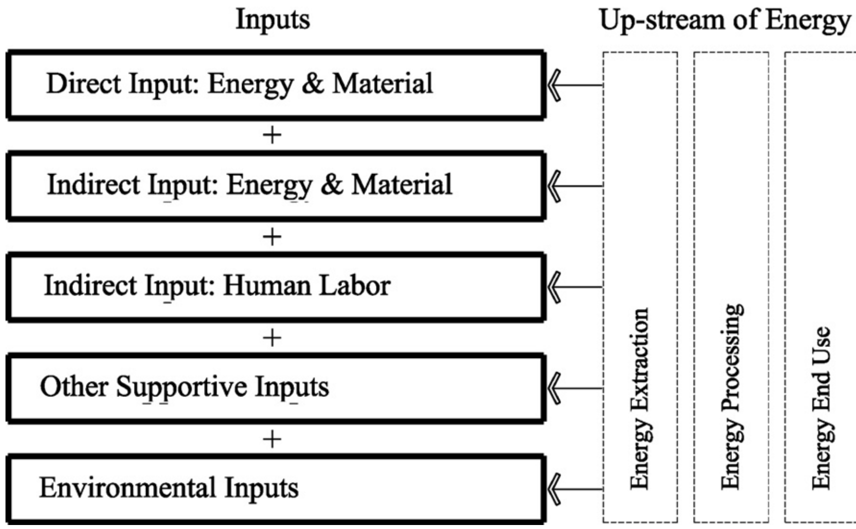

Fig. 5. System boundary for a building proposed by Murphy et al. [93].

Chicago) [15] that includes referring to a variety of literature sources and deriving conclusions. A survey of literature was performed to accomplish this task. The following section provides the results of the literature survey.

4. Findings: conceptual system boundary model

4.1. System boundary model for a building

The literature discussed so far exhibits difference of opinion on system boundary demarcation. Multiple system boundary models with varying boundary lengths and widths are proposed and used by different studies. This section describes the proposed system boundary model based on literature opinion. Some studies [62,63] defined system boundary covering all life cycle stages, whereas others [20,21,32] emphasized how far one needs to go in each of these life cycle stages. This clearly points to two distinct dimensions of a system boundary. One dimension that is longitudinal ("X" dimension) covers a building's life cycle phases, whereas the other, which is cross sectional ("Y" dimension), measures the width of system boundary in upstream and downstream of each life cycle phase. Cross sectional dimension ("Y") may be repeated for each life cycle stage and also for transition from one stage to another.

Studies also differ in the scope of analysis which may be limited to one or more building components such as building envelope and structure or to the entire building. In addition, some studies adopted wider scope covering site, neighborhood and city components such as landscaped areas, walkways, roads, sewerage, storm water system etc. The differing scope levels of studies indicate a third dimension ("Z" dimension) of a system boundary. Fig. 6 illustrates three dimensions of a system boundary for a building. However, the "Z" dimension actually indicates the scope of the study and hence may change across different studies. The "X" dimension along with "Y" dimensions for each stage may be repeated for each scope level in the "Z" dimension.

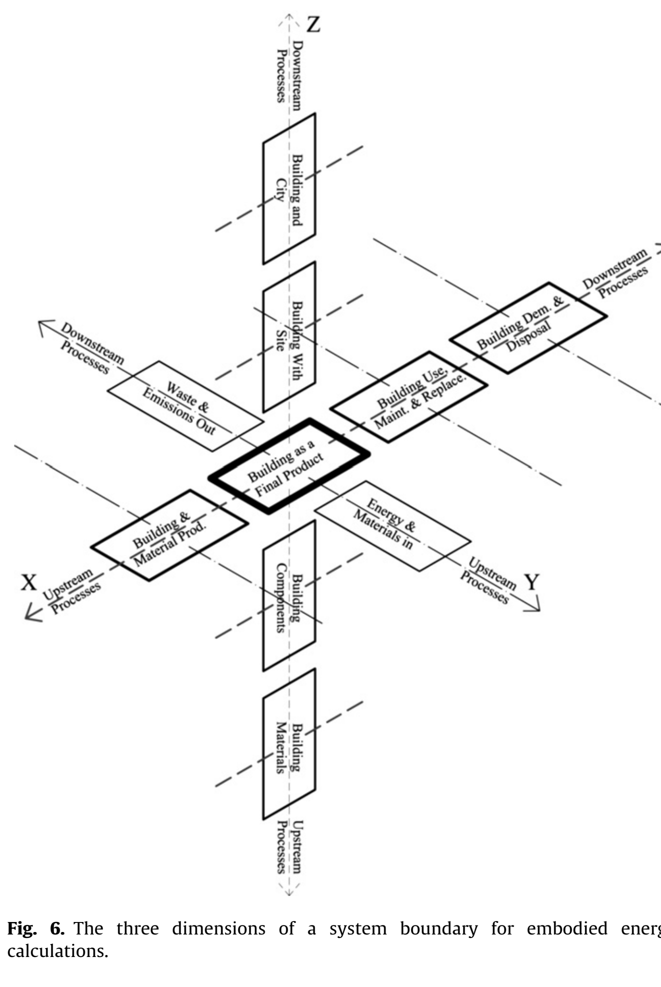

Fig. 6. The three dimensions of a system boundary for embodied energy calculations.

The longitudinal dimension ("X") includes each life cycle stage as one major activity (along with its processes), transition from one stage to another (including transportation) and any recovery of resources and energy between these stages. The starting point in this model is the production of building materials stage (see block "A" in Fig. 7), which involves a production cycle of main production, upstream and downstream processes. Block "A" analysis should be done for each material (building materials, components etc.) and product (equipment, machines and other buildings and structures involved). Each block "A" analysis includes block "B" and "C" analysis, which is explained in a subsequent section.

The cross sectional dimension "Y" covers two sides, one that deals with input (resources and energy) and the other that addresses outputs (waste, emissions, effluents and pollutants) indicating upstream and downstream of process under study

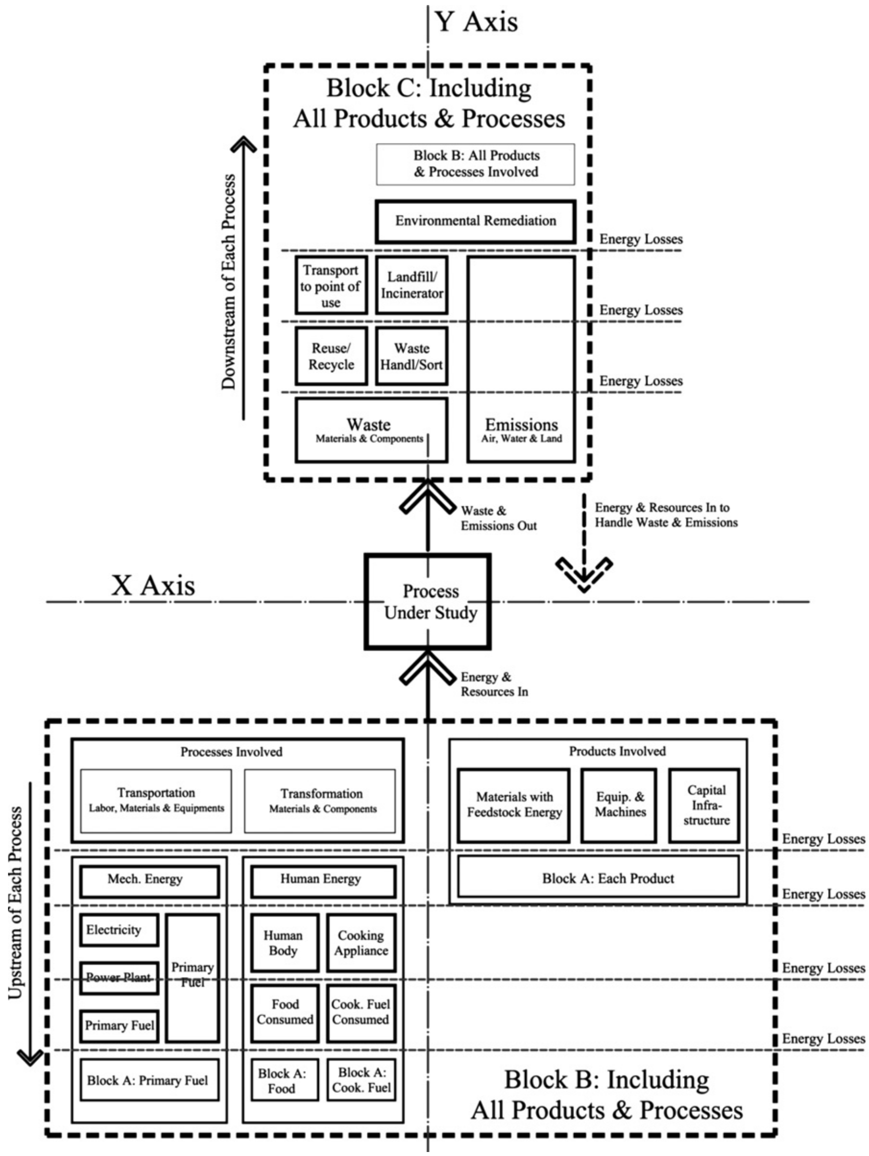

Fig. 7. System boundary in upstream and downstream of each process in building's life cycle stage.

respectively. Fig. 7 illustrates the input and output side as block "B" and block "C" respectively. Input side (block "B") determines inputs of products and processes that are involved in each life cycle stage. The product input category includes feedstock materials (including feedstock energy), equipment and machines, and capital infrastructure (temporary or permanent building or structure) that is fed into or installed for a specific life cycle phase. For each item involved in the product input category, a block "A" analysis needs to be done. The process input category specifies processes of transformation or transportation of input materials. Each of these items in product and process categories consumes resources and energy. Each input and output side incorporates mechanical as well as human energy including possible losses due to acquisition (primary fuel extraction or electricity generation), storage and supply (transmission and distribution of primary or electrical energy). In addition, it also includes losses due to efficiency of equipment or machines and productivity of human labor involved. Block "A" analysis needs to be repeated for each primary fuel consumed by machines and food consumed by labor. The output side (block "C") covers consumption of resources and energy in the remediation of environmental consequences of the input side. Similar to block "B", each item in the product and process category should be tied to block "A" analysis. Hence, we can visualize that system boundary starting with block "A" analysis covers blocks "B" and "C" and finally returns to block "A" analysis at micro level. This may seem an unending process with each block "A" analysis getting relatively insignificant (in terms of its relative impact on the product under study) than the earlier one.

Each life cycle stage of a building incorporates blocks "B" and "C" as shown in Fig. 8, which illustrates a building's system boundary comprehensively. As indicated in the Fig. 8, transition from one stage to another includes each activity of transportation, loading and unloading etc. Hence, blocks "B" and "C" for all products (cranes, trucks, loaders, dumpers etc.) and processes (transportation, loading and unloading) that are involved need to be accounted for in embodied energy calculation. There may be involved two types of recycling or reuse of resources and energy: open or closed loop. Energy may also be recovered from combustion of products that contain feedstock energy (e.g. wood, plastic and other petrochemical products). Open loop recycling covers recycling or reuse between life cycle stages (material or product from one stage is reused or recycled in another stage for the same purpose or as feedstock material) or between industries (material

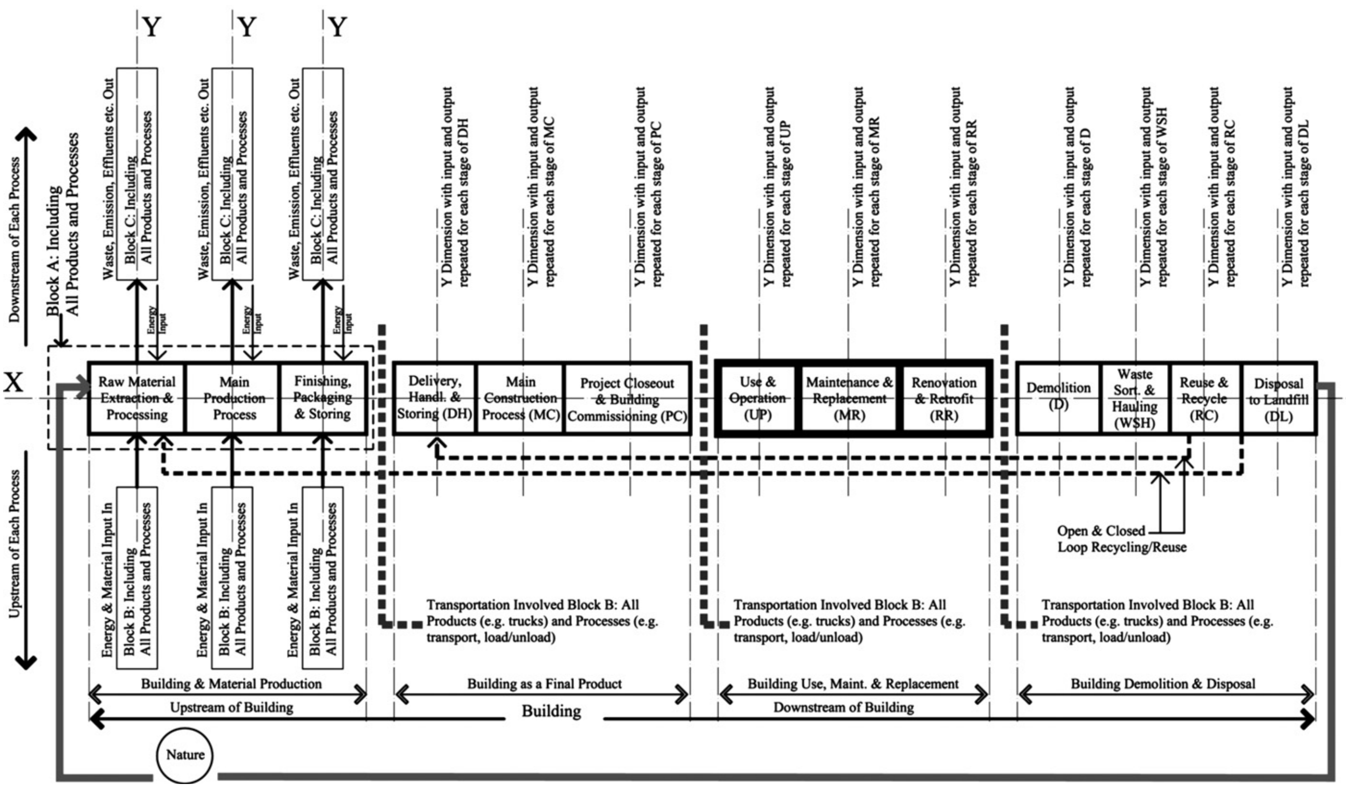

Fig. 8. Proposed system boundary model based on [2,4,20,23,40].

or product from any stage is reused or recycled as the same product or as feedstock material to manufacturing or construction industry). Closed loop indicates reuse or recycling within life cycle stages or industries (material from manufacturing industry is reused or recycled in the same or different industry or material from one life cycle stage (e.g. use and maintenance) is used in the same stage as same or different material).

5. Recommended approaches

The system boundary model proposed and discussed in Section 4.1 demonstrates the literature opinion. A model with such a wider system boundary cannot be completed using only process based data, due to difficult data collection and input tracking. In addition, countries differ in the practices of resource tracking and at the global level it may not be straightforward to include all of the processes described in the recommended model. There could be three approaches to computing embodied energy by covering the proposed system boundary model.

In the first approach, an empirical model can be developed using the average results of case studies published in peer-reviewed journals and conference proceedings. Fig. 9 illustrate a sample framework for an empirical model. Such a model can include factors for amount of energy embodied in materials, appliances and processes of construction, transportation, maintenance, replacement, demolition and waste treatment (reuse, recycle and disposal) as a fraction of the total embodied energy of a building. Similarly it can also include factors of energy embodied in various components of a building and its immediate environment as a fraction of the total embodied energy. There could be different models for different types of construction such as wood frame, concrete frame, steel frame and brick or concrete block masonry. To consider geographic differences, a model for each region (e.g. continent) can be developed. Although the model may not be very accurate, it can provide a reasonable estimate of embodied energy. It can also be used to translate embodied energy data of a building from a narrow to a wider system boundary for a valid comparison or application.

Second, a method to compute embodied impacts can be developed by fusing the process and input/output-based approaches (e.g. input/output-based hybrid approach). Such efforts have been done in the past e.g. [81,95] but they still need improvements such as inclusion of more process data and disaggregation of industry sectors. Moreover, input/output-based hybrid studies calculated the embodied energy of the entire building using data from a highly aggregated industry sector such as residential construction that does not differentiate between a low and a high-cost, a horizontal and a high rise or a modular and a custom-designed structure. We recommend calculating first, the embodied energy of materials and appliances using a hybrid method and then computing the embodied energy of the entire building using the actual quantity of materials, labor and equipment use (process data). Such an approach would help in generating energy estimates specific to the building design and the type of construction. Fig. 10 illustrates this approach. The block "A" includes calculation of energy embodied in material and energy inputs using a hybrid approach. The actual quantity of material, labor, energy and construction equipment use from the bill of quantities then can be used to calculate the total embodied energy of a building. The block "A" can be repeated for each life cycle stage to produce life cycle energy estimates. Another major issue with the input/output data is the temporal representation. Input/output tables are not published frequently and timely and current tables may not present the most recent data [96,97]. A method to translate old input/output data to current economic data can be used to improve its temporal representativeness. The input/output data are published in a producer's and/or purchaser's price and cover a cradle to gate or cradle to site system boundary. The proposed third approach can help include other life cycle phases in the life cycle energy calculations.

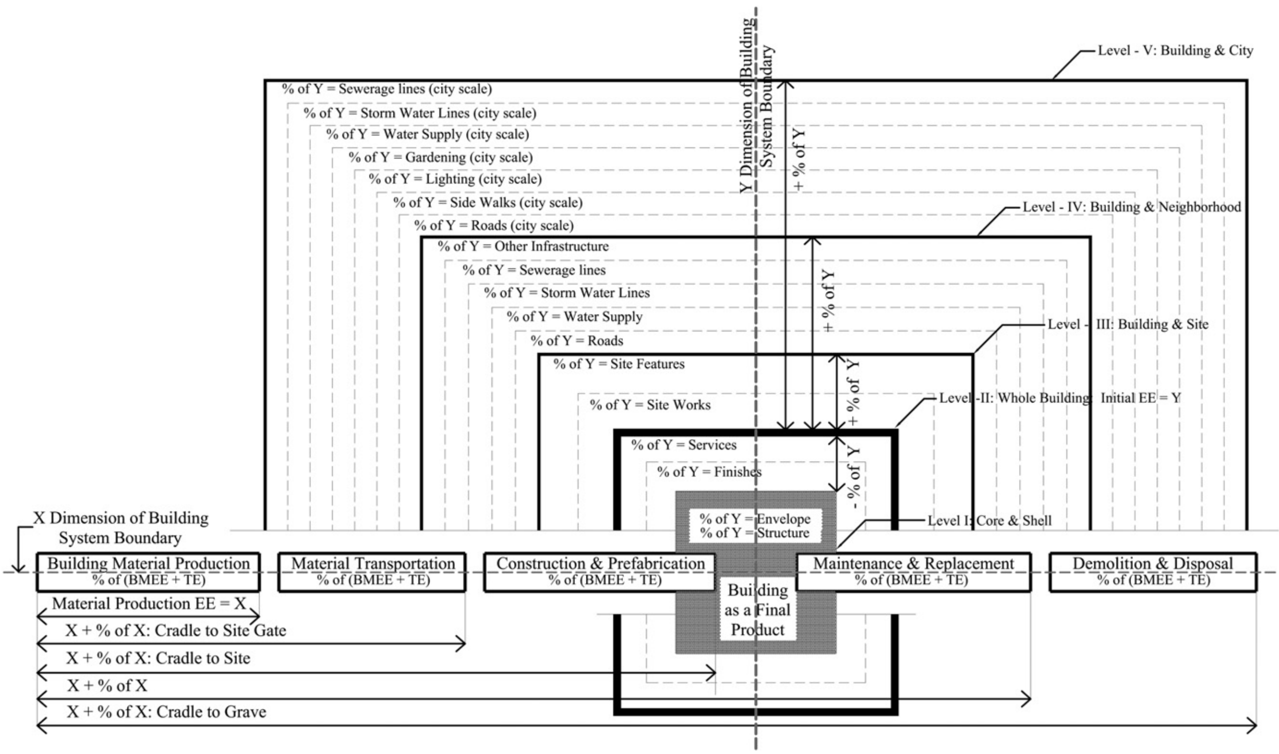

Fig. 9. Recommended sample framework for an empirical system boundary model.

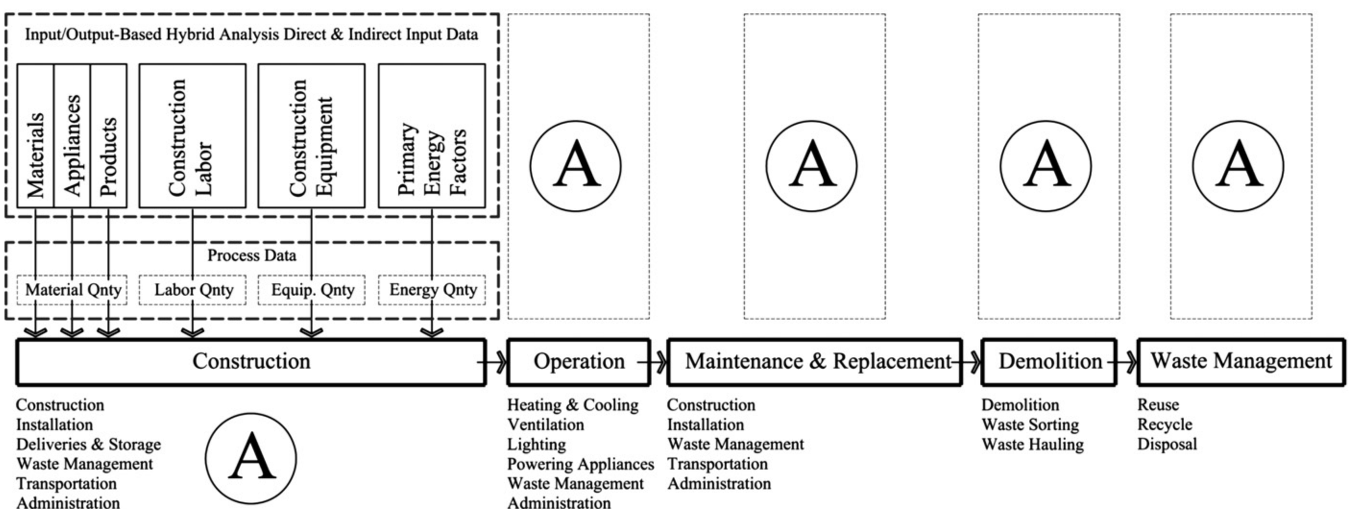

Fig. 10. Recommended approach for an input/output-based hybrid embodied energy calculation.

In the third approach, the relationship of embodied energy and cost can be utilized for estimating the embodied impacts of a building or a building product. Costanza [89] demonstrated a strong relationship between the embodied energy of a product and the monetary output of industry sector that produced it. This is one-way to relate economic data to energy analysis. Literature, (such as [89]), showed a strong relationship of a nation's energy to its Gross Domestic Product (GDP) or Gross National Product (GNP). Costanza [89] concluded that assuming appropriate system boundaries, "market determined dollar values" are proportional to embodied energy values with an exception of the primary energy sector. This conclusion points out another possible approach that could utilize the price of a product to determine its embodied energy. Bullard and Herendeen [98] emphasized the relationship of product consumption and energy consumption by stating "when you consume anything, you are consuming energy." Likewise in a recent study, Langston and Langston [11] concluded that the initial embodied energy of a building is strongly correlated with its capital cost at the project level. However, when analysis is done at a more detailed level (individual work and material level) this correlation weakens.

More research is needed to accomplish the system boundary model derived and proposed in this paper. With existing energy analysis methods, it can be argued that completing the proposed system boundary model may not be straightforward looking at difficult tracking of energy and material inputs. As discussed in the third approach, a building and its material cost may be used to estimate direct as well as indirect energy consumption comprehensively. In addition, costs usually take into account most of the inputs as well as handling and remediation of outputs (e.g., waste,

pollution and emission) and therefore may provide a reasonable estimate of indirect energy consumption.

6. Summary

Energy embedded in a building and its components is important and with a quest for net-zero energy buildings, its significance is expected to grow. However, this field of research still suffers from inconsistent, inaccurate and incomplete data owing to numerous parameters. System boundary definition is the key parameter which differs and causes problems in embodied energy results. In the past, studies have defined the system boundary subjectively due to either differing scopes or limited data availability. Their results may be suitable to their differing scopes but they may not be comparable to other studies due to differing system boundaries. The results of such studies cannot be fully utilized by the construction industry professionals and researchers due to a lack of comparability.

Studies have been proposing various system boundary models for the life cycle assessment of a building since 1970s e.g. [40]. These models vary in terms of their emphasis. Some models are generic and emphasize a typical life cycle of a building. Other models are more specific and are focused on detailed analysis of one or more upstream and downstream processes. In this paper, a conceptual system boundary model was proposed based on the review of relevant literature. This model simplifies various intertwined processes by categorizing and arranging them in three distinct dimensions. Most of the life cycle energy aspects that have been suggested by the literature were included in this model. An analysis of embodied energy of a building can be performed utilizing this model in a clear and comprehensive manner. Also, three approaches to calculate embodied energy by covering the proposed model are recommended.

7. Future research

The next step would involve developing the recommended approaches into three calculation methods and validating their results by performing case studies.

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